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A SUBSIDIARY OF Ford Motor Company

SCIENTIFIC LABORATORY • Blue Bell, Pennsylvania

Mitchell 6-9100

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TO: NASA Headquarters
Washington, D. C., 20546
Attention: Code RET

SUBJECT: Theoretical and Experimental Investigation on Modulation Inducing Retrodirective Optical Systems, Contract NASw-721 (10-804) (10-1227), (Philco B003), Monthly Progress Report No. 11 for the period of 21 March 1964 to 1 May 1964

MEETINGS BETWEEN CONTRACTOR PERSONNEL AND TECHNICAL SUPERVISOR

The Philco Scientific Laboratory at Blue Bell was visited on April 20 by Dr. Roland Chase of NASA Headquarters, Washington, D. C., and Dr. Henry Plotkin of Goddard Space Flight Center, Greenbelt, Md. Philco personnel attending the discussion of the MIROS program were Dr. M. E. Lasser, Dr. B. W. Harned, G. W. Racette, and A. Mace. Work on optical pumping and band edge shifting was described, and the optical pumping model with its three methods of cross modulation was displayed. The discussion was concerned mainly with feasibility of the passive MIROS system. It was concluded that further numerical estimates of optical pumping capabilities for the space operation are desirable.

SUMMARY OF WORK ACCOMPLISHED DURING THE REPORT PERIOD

Preliminary attempts to observe transmitted light in the cesium optical pumping experiment with high resolution equipment have successfully shown the desired variations in intensity when magnetic field is varied. Radio frequency resonances in the excited state were sought without success when making use of D_2 radiation in pumping and cross modulation. Our early proposal of using free carrier absorption as a MIROS principle has been investigated in more detail. It is concluded that small carrier generation discourages experimental feasibility studies.

EXPERIMENTAL ACTIVITIES

Optical Pumping

Microwave work mentioned in the last report has been continued in an effort to observe the ground state resonances of cesium. The desired quantitative modulation frequency response measurements have not been undertaken. Careful measurement of minimum detectable microwave power for the resonance depumping is of particular interest in order to determine the relative values of optical pumping power and microwave modulated power. Preliminary attempts to set an upper limit on the required microwave level have shown rather high values, but sources of error in the method are numerous. Because of the photon nature of the process, one would expect that the microwave power required would be considerably less than the optical pumping power. This has not been the case in these early estimates. But the unknown factors are the actual power output of the oscillator and the actual power arriving at the center of the absorption bulb. The possibly large variations in coupling could account for the discrepancy.

Variations in intensity of transmitted cesium pumping light have been observed with our high resolution equipment. The pumping light was aligned with the f/17 B & L grating spectrograph and a small (1-inch diameter) Fabry-Perot interferometer placed between source and slit. With the absorption bulb in place before the interferometer, one may observe changes in intensity of the fringe pattern (as seen on an RCA 6676 image converter tube) when the magnetic field is switched on and off. With a photomultiplier detecting the 8943 Å pumping light and the interferometer not in place, increases in transmission of as much as 50 percent could be observed when the magnetic field was switched on. The temperature of the pumping lamp affected the relative absorption values in a manner not observable with this viewing method; but, generally, operation was maintained at about 30-percent transmission increase with magnetic field, as observed with an oscilloscope. The spectrograph resolution is not good enough to allow separation of the hyperfine components of the 8943 Å line, but use of the Fabry-Perot did allow an indication of resolution in spite of the 1000-micron slit required.

One would expect with this combination the line images to be superimposed, and the fringe systems of each line to be slightly separated along the lengths of the lines. It appeared as though field-on conditions caused one set of fringes to brighten at the expense of the other. This would be explainable if the F = 4 level were populated in the ground state to cause a transmission increase. The apparatus was reassembled without the spectrograph, and only filters were used. The fringe system was easily obtained, particularly with a plate separation of the Fabry-Perot of about the required 0.83 cm to allow the fringes of one line to fall midway between the fringes of the other line. As the magnetic field is turned up from zero value, one can observe changes in intensity and in width of the fringes. The images of the fringes on the image converter are rather poor in contrast, partly because of the large intensity losses in the interferometer and fringe imaging system. However, there was no doubt of intensity changes in one fringe system which were more outstanding than in the other fringe system. This corresponds to alternate fringes changing in intensity as the field is varied, indicating that the supposed pumping of the F = 4 level of the ground state does occur to produce a greater transmission as the field is increased. It was hoped that structure of the fringes could be observed, but as yet this finer resolution has not been attained. This resolving of the 8943 Å hyperfine multiplet in the presence of optical pumping apparently has not been done by other workers in the field, and it hoped that a better understanding of the process leading to new techniques using the principle may be possible.

An interesting paper by Russian scientists on field reversal effects in optical pumping appears in the Proceedings of the 3rd Quantum Electronics Conference, "On Dehmelt's Experiment," by E. B. Alexandrov and V. A. Kchodovoj, p 299 in Quantum Electronics III, Columbia University Press, 1964. The contention of these authors is that a change in magnitude of the aligning field to produce reversal of direction, if more rapid than the time to relax spin orientation, cannot change the magnitude of optical absorption of the system. Proceeding with a careful experiment to cancel stray fields and then to reverse the alignment field direction with pulses of varying rise time, these authors found that absorption changes follow in accordance with relaxation times. What this amounts to in cross modulation applications is that an effort to increase frequency response by field reversal over that of other methods ought not to be successful if uniform aligning fields are present. The effect of stray fields on the field reversal method appears at zero value of the aligning field in the sense that the pumped atoms try to precess around the stray field direction and result in system disorientation.

The net result of these stray fields is therefore an effective decrease in alignment (relaxation) time of the pumped atoms. These Russian workers, therefore, contend that an experiment using field reversal to measure relaxation times is not meaningful unless stray fields are cancelled. If such be the case, it is clear that stray fields act in the same sense as a decreased relaxation time in aiding higher frequency response in cross modulation experiments.

In the Proceedings of the 2nd International Conference on Quantum Electronics, "Advances in Quantum Electronics," Columbia University Press, 1961, E. Lipworth (p 293) proposes a method for enhancing optical pumping double resonance signals by making use of transitions in excited states. The suggestion is to make use of cesium, pumping with circularly polarized D_2 radiation, simultaneously applying an RF-field to induce transitions in the $^2P_{3/2}$ state from the F = 5, m_F = 5 to the F = 4, m_F = 4 state. Recall that ordinarily the D_2 line is not recommended for optical pumping of cesium because of the possibility of absorbing radiation in the (4, 4) ground level and thereby reducing the selective population of this level. If the atoms are excited to the $^2P_{3/2}$ (5, 5) level, the selection rules in spontaneous emission force return to the ground state (4, 4) level. Transitions out of the (5, 5) level into the (4, 4) level of the excited state will therefore affect the light transmitted through the absorption cell. K. Althoff[1] in a fluorescence experiment has measured the energies of transition between levels of this $^2P_{3/2}$ excited state. These are given as: F = 2 to F = 3, 49.9 mc/sec; F = 3 to F = 4, 66.45 mc/sec; and F = 4 to F = 5, 82.85 mc/sec. RF fields of about 1 gauss were used by Althoff to induce the transitions.

The above technique was considered worth investigating to determine the possibility of altering the transmitted light in the cross modulation experiment. Although some time was spent trying to observe changes — particularly the most intense 5-4 transition at 82.85 mc/sec — none could be seen. It was hoped that some determination of the degree of mixing in the excited state could be arrived at when pumping is effected with 8943 Å (D_1) light. Various modifications of this experiment were made, all admittedly with small rf-energies,

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1. Althoff, K., Zeitschrift fur Physik, 141, 1955, p 33-42

using various polarizations and filtering. The variations predicted in the Lipworth paper for cesium vapor transmission make it appear as though a sizable effect should be observed, and lack of success at this point is not readily explainable.

It has been stated that greater frequency response in cross modulation should be observed with more intense pumping. The theoretical discussion in the March 9 report shows this to be true for the simplified model, where the modulation signal is reported proportional to $P/(P^2 + \omega^2)^{1/2}$, P being the pumping rate and assumed to be much greater than the relaxation rate and equal to the depumping rate. The value of ω at which the signal falloff is one half, in this simplified expression, is 1.7P, i.e., directly proportional to P. The beginning of the ω^{-1} falloff, as predicted by our theory, in past experiments with pumping power of a few microwatts occurs at about 100 cps. If we were to extend this frequency by a factor of 10^4 to 1 Mc/sec, we should have to increase the pumping power to a fairly large fraction of a watt. It seems reasonable to conclude that the inverse relationship between required light power and bandwidth will always be true for atomic MIROS elements, as generalized from the expression for absorption constants proportional to $Nf/\Delta\nu$. Here $N = G\tau$, N the number of atoms susceptible to modulation signals, G a generation rate, τ the lifetime of these atoms in their receptive state, f the so-called oscillator strength of maximum value unity, and $\Delta\nu$ a line width assumed to be acceptably substituted by the bandwidth desired in the communication system. The reciprocal relation between G, the generation rate (pumping power), and $\Delta\nu$, the bandwidth, apparently cannot be violated; but it does, fortunately, provide us with the information that we can go to higher bandwidths if we wish to pay the penalty of additional input power.

Free Carrier Absorption

In 1959 an electronic infrared imaging system was designed and constructed by members of the Philco Research Laboratories.[2] This system was based on the principle of alteration of absorption of infrared light by alteration of free carrier density in a silicon filter. In this apparatus an electron gun provided a beam of electrons which could be

2. M. E. Lasser, P. H. Cholet, and R. B. Emmons, "Electronic Scanning System for Infrared Imaging," Proceedings of the IRE, 47, 2069, 1959

scanned to provide a raster at the silicon. Penetration of the electrons into the silicon allowed hole-electron pairs to be generated in sufficient quantity to allow appreciable free carrier absorption of infrared radiation incident at the location of the electron beam impact spot. Display of the detector signal on an oscilloscope proved the device an effective IR scanning system. In Philco Proposal R63-7 concerning the MIROS study program, it was suggested that the same principle of free carrier absorption could be used for the proposed cross-modulation application in which the free carrier injection would be accomplished by one of the light beams. A review of the published literature[3, 4, 5] has disclosed some analytical and experimental information on the subject, including a very timely effort[4] to produce modulation by this technique.

In the McQuistan and Schultz work, carriers were injected electrically, using broad-area junctions of alloyed indium onto germanium. Direct bias current densities of 2 amp/cm^2 and alternating current densities of about 1.5 amp/cm^2 were used to control the transmitted light from a Nernst glower at wavelengths of 2 to 12 microns. These authors define modulation efficiency as the amplitude of the modulated fundamental of the radiant power normalized to the ideal value of the sinusoidal modulation of all the radiant power incident on the modulator. These efficiencies depend on the minority carrier (hole) lifetime. A modulation index is also defined as a measure of the amplitude of the fundamental of the modulated radiant power normalized with respect to the radiation transmitted when no ac signal is present. This particular figure of merit would be of interest in a MIROS application. Relative modulation index of 10^{-3} to about 0.7 is plotted versus injection current density from 10^{-2} to 10 amp/cm^2, indicating, as one would conjecture, a linear relationship with increasing carrier concentration (current), and showing very encouraging modulation capabilities at

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3. F. Desvignes, "Optical Absorption by Free Hole-Electron Pairs Liberated by the Photoelectric Effect in a Germanium Single Crystal," C. R. Acad. Sci (Paris), vol. 246, no. 12, 1824-7, March 24, 1958

4. L. Huldt, "Determination of Free Carrier Lifetimes in Semiconductors from the Relaxation Time of Photo-excited Infrared Absorption," Arkiv för Fysik, 15,229-36, 1959; also Ark. Fys. 20,527, 1962

5. R. B. McQuistan, and J. W. Schultz, "Modulation of Infrared by Free Carrier Absorption," J. Applied Physics, 35, April 1964, p 1243

the higher levels of operation. These authors showed that relative modulation efficiency versus wavelength increases irregularly from 1.0 to about 1.8 for wavelengths increasing from 2 to 12 microns. The preferred range of operation, according to this curve, is from about 7 to 12 microns. Experimental modulation results show a good fit to an expression derived for the modulation index varying as $(1 + \omega^2 \tau^2)^{-1/4}$ for two values of τ_p, minority carrier lifetime of 40 and 0.6 microseconds. Flat responses for these samples are observed to about 2500 and 10^5 cps, respectively. For a given carrier injection current, the modulation efficiency increases with lifetime, while the response falloff frequency decreases.

Huldt's determination of free carrier lifetimes is interesting in the MIROS application because of the similarity in technique. Huldt irradiated a silicon and germanium sample with chopped light from a tungsten source (up to 4800 cps) and observed changes in infrared transmission which was chopped at 13 cps. A slow detector was used and was assumed to measure the mean value of transmitted light over several periods of the chopped carrier injection light. For a germanium sample of 50-ohm/cm, resistivity at 11-microns wavelength, a hole lifetime of 165 microseconds was deduced from the data. A curve of transmittance versus chopping frequency shows a falloff at about 300 cps in agreement with theory developed by Huldt and in the McQuistan and Schultz paper.

In the production of free carriers by low energy photons, one would assume that perfect efficiency would provide one pair per photon, in contrast to the estimated 2000 pairs per high energy electron in the infrared scanner of Lasser, Cholet and Emmons. These authors used a blanking spot area on silicon of about 3×10^{-4} cm^2 and 0.5 ma current at 25 KV. An equivalent photon flux would be of the order of 10^{22} photons/cm^2-sec or a few kilowatt/cm^2 power densities at the wavelengths of interest. With laser sources in the laboratory, this value of light flux is easily attainable, and the substitution of a laser beam for the electron beam in the infrared scanner is a logical suggestion. However, transmission of power of this magnitude to a satellite at long distances in other than short pulses requires lasers of far greater capacity than presently available. One, therefore, is forced to conclude that the concept of cross-modulating using free carrier absorption is practicable in the laboratory, where high photon fluxes are possible, but virtually impossible in CW operation for long distance satellite optical communications work.

PRINCIPAL INVESTIGATORS' TIME DEVOTED TO WORK

The principal investigators performing the work and the time they devoted from 21 March to 21 April 1964 are listed below:

Personnel	Man-Hours
B. Harned	104
L. Leder	22

Mr. Leder has been transferred to another Philco location and has terminated his association with this project, effective 15 April. Dr. Harned has been devoting 3/4 of his time to the project from 21 April to 1 May, the time of this report.

PLANS FOR THE NEXT INTERVAL

It is expected that modulation characteristics of the microwave portion of the optical pumping experiment can be investigated during this period. Further investigation of the fine resolution experiment appears to be of interest with greater magnetic field intensities. If time permits, the excited state resonances will be reinvestigated.

B W Harned

B. W. Harned
Senior Research Specialist

M E Lasser

M. E. Lasser
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